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Does climate influence energy demand? A regional analysis

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HIGHLIGHTS

- Impact of distribution of climate on regional sectoral energy demand.
- SUR with commercial, industry, residential and transportation energy demand functions.
- Upside and downside first and second moments of temperature and precipitation.
- Empirical application involved panel data, 48 states from 1970 to 2014.
- Energy demand cross-price elasticities (CPE) and Allen elasticities of substitution (AES).

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ABSTRACT

The duality of cost minimization is used to examine the effects of climate change on US sectoral climatic regional energy demands from 1970 to 2014. The first order conditions of transcendental logarithm cost function provide sectorial compensated demands for energy. A system of demand share equations or sectorial compensated demand for energy is explained by exogenous prices, technology and distribution of climatic variables i.e. temperature and precipitation is estimated. The distribution includes the downside and upside first moment, i.e., mean and downside and upside second moment, i.e., variance. The estimated parameters are used to construct energy demand cross-price elasticities (CPE) and Allen elasticities of substitution (AES) for nine climatic regions. The Southwest, Northeast, and South are sensitive to rainfall distributions especially the transportation and industrial sectors while the Northeast, Central, and South are affected by temperature variations affecting residential and industrial sector energy use. The commercial sector uses the least energy because of improved technological changes. Consequently, there are high substitutions of commercial energy for both residential and industrial. The transportation sector has the least price and technical substitutions.

1. Introduction

Researchers [1–3] have looked at the impacts of increasing temperature. An increase in the average temperature led to climatic drought risks [4], coastal flood risks [5] and human health risks [6,7]. Parry et al. [8]; and Warren [9] warned of the impacts of increasing average temperature on the ecosystem. Cline [10,11] conducted a cost-benefit analysis of climate change, considering environmental loss, human life, disaster, water supply and so forth. Climate models predict a range of changes to temperature, precipitation and other climate measures. Most models predict a significant increase in global average temperatures by the end of the current century for scenarios close to a business as usual emission path or a slightly more optimistic path. Auffhammer et al. [12] presented a detailed discussion of climate models and their use in social science. Other empirical estimates of climate sensitivity analyses involve estimating economic impacts on a specific sector, like agriculture [13]. Using micro-level and region-specific data, the importance of climate on energy demand by the commercial, industrial, residential and transportation sector is well established [14–21]. Energy use in commercial, industrial, or residential buildings for example, is one of the largest contributors to global and local energy consumption. Many studies have looked at the impact of building variables on energy use [22–27]. Zhu et al. [28] proposed a time-for-space substitutional model, which evaluates the variations of residential buildings' energy consumption in China driven by seasonality, climate, and socioeconomic factors.

The energy demand by sector has been the focus of the Office of Energy Information Administration in the United States' Department of Energy. The pressing issue in the current energy policy debate is keeping up with the increasing demand from commercial sector (CS),

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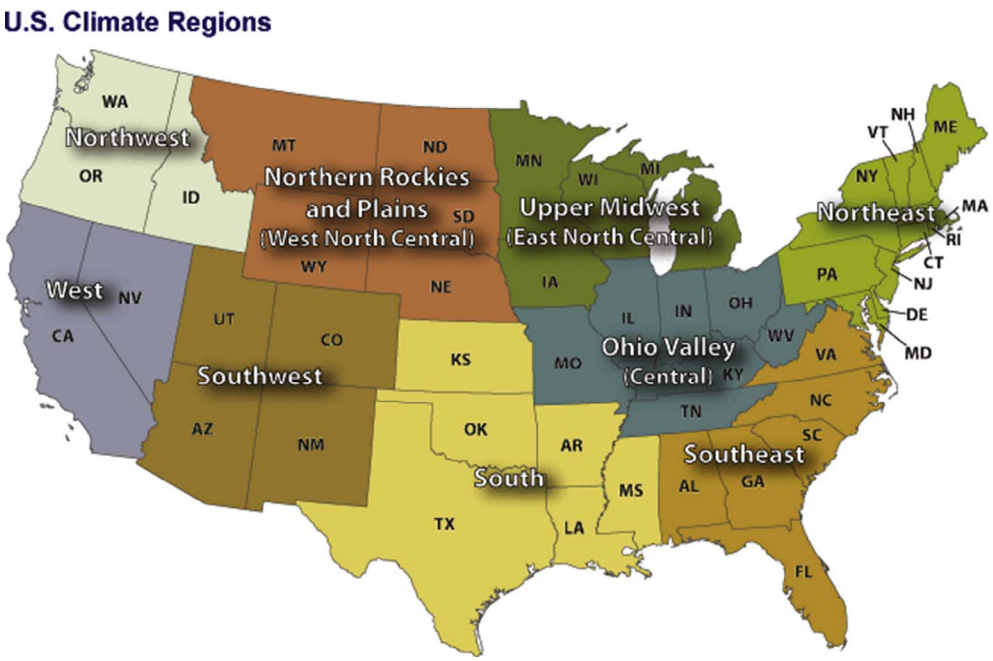

Fig. 1. U.S. climate regions used in the analysis.

industrial sector (IS), residential sector (RS) and transportation sector (TS). Energy demanded by each of the four sectors is unique and influenced by economic activity, climatic conditions, and decisions of individual states within nine climatic regions (see Fig. 1) across the U.S. Due to the difference in climate patterns between states across climatic regions (National Oceanic and Atmospheric Administration define the climatic regions), there is a need to conduct climatic regional analysis. The effect of each sector's energy demand is typically used to predict the cost of climate change adaptation. Analysis of sectoral energy demand is based on the first order conditions derived from non-Hicks neutral technology assumption of cost function. Theoretically, the first order conditions or system of sectoral energy demand equation include prices paid by a sector and technological changes using seemingly unrelated regression (SUR) statistical technique. The cost function is extended to include climatic variables that are outside the control of sectors using energy. The novelty of this extension is to evaluate the importance of climate on sectoral energy demand. Output from SUR are used to validate the substitution or complementarity between the sectors demanding energy using price elasticities. Most of the earlier studies estimated the energy demand considering price and technology changes (references in the next section).

Extending the climate-energy use and energy demand literature, our research contributes by evaluating the importance of the distribution of temperature and precipitation on energy demand by commercial, industrial, residential and transportation sectors simultaneously using panel SUR model. The distribution includes the first moment, i.e., mean and second moment, i.e., variance. To evaluate the importance of observations above and below the average, the overall mean and variance are further decomposed into downside and upside mean and variance. The downside mean and variance is based on observations below the 30-year average, while the upside mean and variance is based on observations above the 30-year average. These variables capture the effect of negative and positive observations on energy demanded by the four sectors, instead of point estimates or extreme points. For example, does the temperature or precipitation deviation below the average have a similar or opposite effect on energy demand compared to deviations above the average? This will help not only draw inference between climate regions based on the results but will also help develop policies to address the climatic-energy demand.

As part of the second contribution, regional energy demand analysis, cross-price elasticities (CPE) and Allen elasticities of substitution (AES) are estimated for nine climate regions to account for potential differences in climate, i.e., temperature and precipitation. The parameter coefficient estimated from the system of sector energy demand equation are used to develop CPE and AES. The AES stand for purely technical substitution possibilities while the CPE includes income effects and therefore reveals potential economic substitutions. The CPE and AES estimates are the first of its kind that take into account the downside and upside first and second moments of temperature and precipitation.

The final contribution of this paper addresses potential differences in regional climate impacts on the energy demand equations. The results from nine climatic regions of the U.S. includes the non-climate change energy demand term (intercept); the effects of technological change on energy demand (trend variable); the effects of all eight climate change variables; and both economic and technical substitution potential by-sector and by-region.

To summarize, the primary goal of this study is to find the influence of climate, i.e., average and variance of temperature and precipitation associated with negative deviations (downside) and positive deviations (upside) on energy demand at the U.S. climate regions using state level data in the U.S. from 1970 to 2014. Employing the transcendental logarithm cost function, a system of residential, commercial, transportation and industrial sector energy demand functions explained by prices, technology and climate as exogenous variables are estimated. Second, the estimated parameters from the system of demand equations are used to construct price elasticities and Hick-Allen elasticity of substitution for energy demand by U.S. climate regions. The findings of this study will be relevant in the development of a comprehensive energy policy across nine U.S. climatic regions based on the changes in the energy demand by residential, commercial, transportation and industrial sectors accounting for technology, price, and climate change. Hence, the use of panel SUR statistical technique is new in the estimation of sectoral energy demand that includes theory based variables (price and technology) and distribution of climatic variables.

The paper is organized into five sections. Section 2 is a brief review of empirical studies on the role of climate on the energy demand, price, and technical substitution. Section 3 presents the theory and methods employed in the analysis. The results of the analysis and its discussions are presented in Section 4 while Section 5 presents the conclusion.

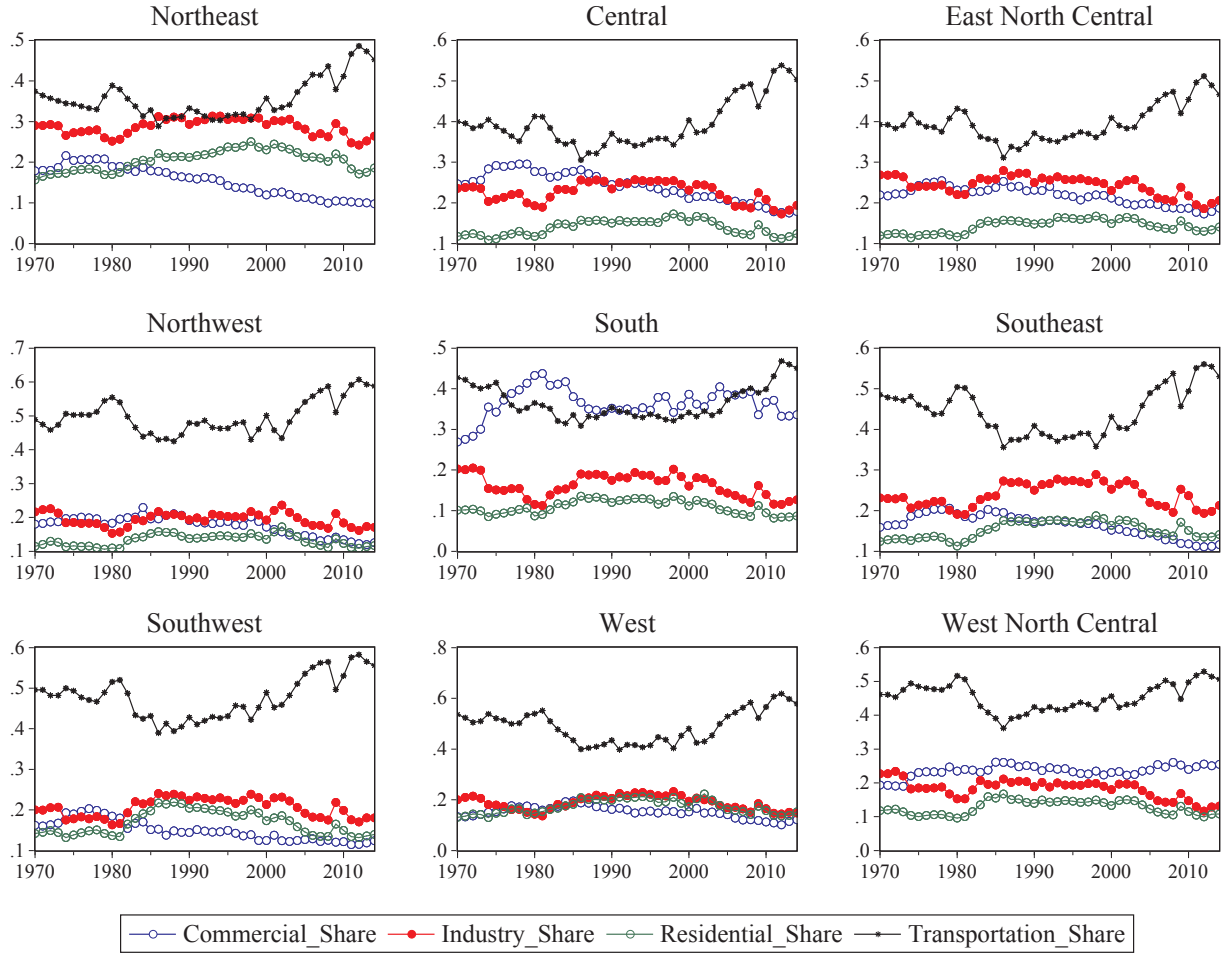

Fig. 2. Average demand shares by sector and region, 1970 to 2014.

Table 1
Summary statistics of the prices, shares and climate variables.

	Mean	Median	Maximum	Minimum	Std. Dev.
			Prices		
Commercial	5.974	4.152	31.566	0.239	5.601
Industry	12.485	9.907	86.069	1.244	11.765
Residential	16.282	15.892	34.856	2.535	7.897
Transportation	10.939	8.589	29.709	2.070	7.441
			Shares		
Commercial	0.206	0.191	0.438	0.097	0.072
Industry	0.214	0.209	0.314	0.112	0.044
Residential	0.150	0.145	0.251	0.081	0.034
Transportation	0.431	0.426	0.618	0.289	0.072
			Climate variables		
Mean precipitation Downside	0.060	0.054	0.148	0.008	0.034
Mean precipitation Upside	0.091	0.103	0.232	0.016	0.055
Variance precipitation Downside	0.396	0.349	1.007	0.014	0.262
Variance precipitation Upside	2.228	1.819	6.776	0.033	1.581
Mean temperature Downside	0.512	0.373	1.991	0.077	0.376
Mean temperature Upside	0.534	0.465	1.595	0.148	0.271
Variance temperature Downside	621.1	396.8	2924.8	149.9	571.0
Variance temperature Upside	773.4	551.5	2849.9	86.6	577.9

2. Review of empirical studies in energy substitution

Studies conducted on energy substitution include works by Griffin [29], Caloghiro et al. [30], Barnett et al. [31], Kemfert [32], Mahmud [33], Kuper and Soest [34], Thompson [35], Roy et al. [36], Koetse et al. [37] and Thompson [38]. Most of these studies assessed factor substitution between non-energy inputs specifically labor and capital and energy inputs in different non-energy industries [39–45]. Most of these studies employ panel data and use log linear and transcendental logarithm production functions to estimate the price and cross price elasticities of both energy and non-energy inputs under consideration with the main industries of focus being the non-energy production and manufacturing industries.

Caloghiro et al. [30] and Barnett et al. [31] find electricity to be a weak substitute for capital and labor, implying electricity subsidies lower the demand for capital and labor. In Pakistani manufacturing, Mahmud [33] employed the partial equilibrium method of analysis and found weak substitution between electricity and natural gas although there was a slight substitution between aggregate energy and other inputs. Also, Kemfert [32] employed three different nested CES production functions to estimate the substitution effect between energy, labor and capital inputs and reported that in the long run aggregate energy, capital and labor are substitutes in West German manufacturing industries. Although these studies have proven that energy and capital are substitutes. Hunt [39] in studying the UK industrial sector, found capital and energy complement capital and labor as well as being substitutes. To solve this dilemma of conflicting findings, Chichilnisky [40] employed the general equilibrium model to analyze energy- capital substitution and concluded that whether energy and capital are

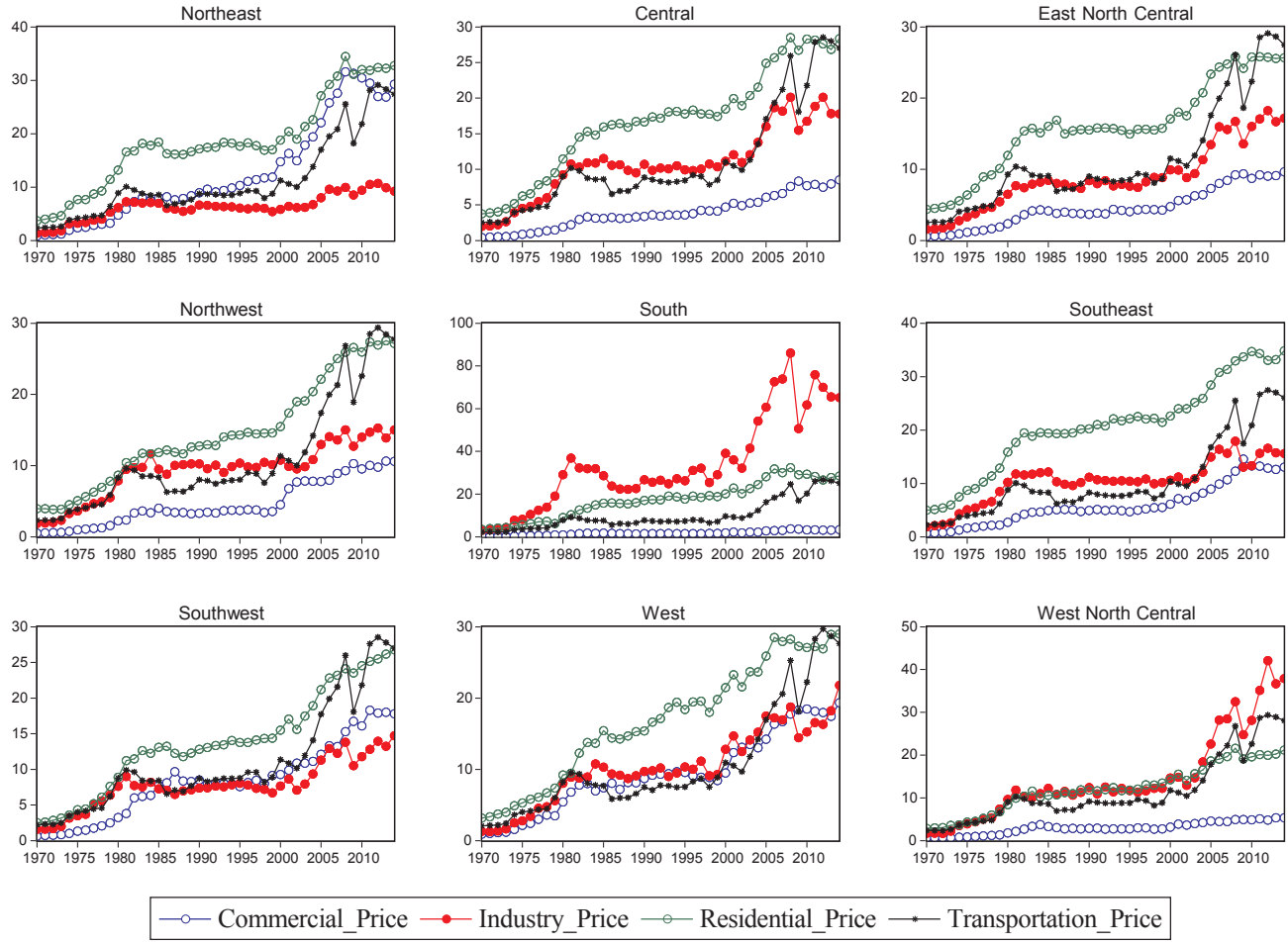

Fig. 3. Average prices of energy by sector and region, 1970 to 2014.

complements, or substitutes depended on the parameters of the model and the price of energy. Alternatively, the study that considers the substitution of energy inputs in the energy industrial is by Griffin [29]. Employing pooled international sample data to the transcendental logarithm production function, Griffin [29] estimates the inter-fuel substitution relationship between fossil fuels (coal, gas, and residual fuel oil) in the generation of electricity. His findings suggest a greater possibility of substitution among the three energy inputs in the generation of electricity.

These reviews reveal that not much research has been conducted on the substitution of energy use by different sectors as compared to the substitution of energy inputs and non-energy inputs in non-energy industries. In terms of energy generation, most studies focus on the environmental impact of switching energy inputs [41–44] with few studies [29] focusing on the possibility of substitutability between energy inputs in the energy industrial. This study therefore addresses this issue by figuring out the potential substitution between electricity and other energy input forms in the U.S. electricity generation.

Regional energy demand sensitivities to climate and climate change. Several methodological papers have focused on the historical relationship between climatic and weather conditions and energy demand at the state, regional, or metropolitan levels [45–47]. For many reasons, Barron [47] argues that for policy analyses, energy demand sensitivities to climate and climate change should be performed at a regional scale. First, global climate change is expected to have a geographically distinct impact. For example, global climate models predict that the Northeast region of the U.S. will experience the lowest rate of warming relative to other regions of the country. Consequently, analyses that apply a uniform temperature increase over the entire continent or nation may miss important geographic impacts on energy use. Due to its large geographic extent and heterogeneous climate, the ability to capture and interpret geographical variations in the climate change impact on energy systems is particularly important for the U.S.

A second justification for carrying out regional analyses lies in the regional difference in energy infrastructures [48]. Regional energy systems differ in terms of energy sources, efficiencies and characteristics of supply and conversion of infrastructure, age of transmission and distribution systems, end use technologies and characteristics of end users.

The third justification concerns sectoral differences in energy demand. For example, Sailor [49] observes a significant different variation in sectoral demand sensitivity between states. He finds a temperature increase of 2 degrees Celsius is associated with a 11.6% increase in per capita electricity used in Florida and a 7.2% decrease in Washington. Even in neighboring states, such as Florida and Louisiana, residential and commercial sensitivities are noticeably different. Similarly, Sailor and Munoz [45] and Sailor et al. [46] found considerable variations in in-state level electricity and natural gas consumption to temperature variables. Warren and LeDuc [50] statistically relate natural gas consumption to prices and heating degree-days in a nine-region model of the U.S. and find noticeable regional differences. Scott et al. [51] use a building energy simulation model to assess the impact of climate change on commercial building energy demand in four U.S cities (Seattle, Minneapolis, Phoenix, and Shreveport). Each city was found to have a unique response to climatic changes with, for instance, a 7 degree Fahrenheit increase in daily temperatures increasing the cooling energy use 36.6% in Phoenix and 93.3% in Seattle.

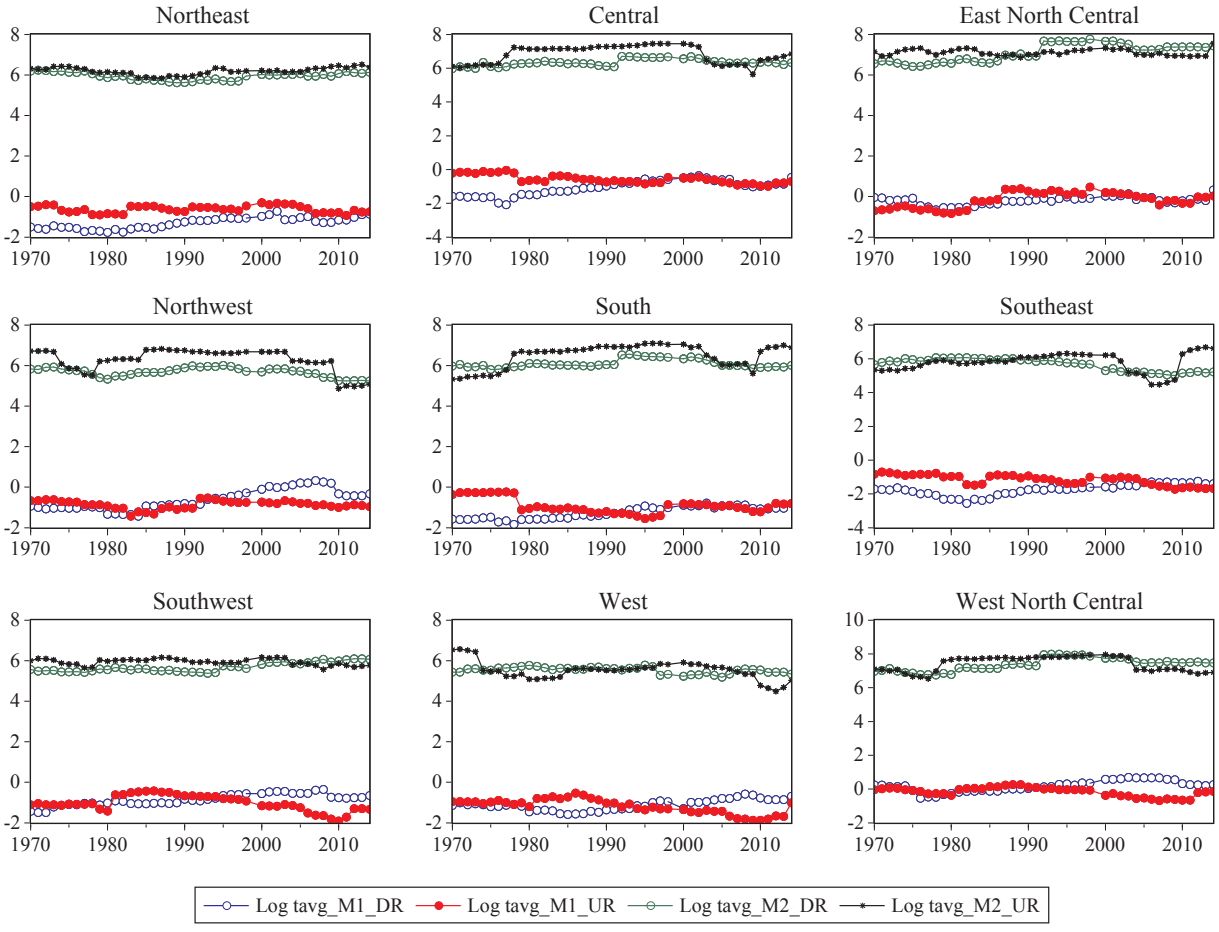

Fig. 4. Average and variance of downside and upside temperature, 1970 to 2014.

3. Economic framework

The duality of maximizing utility and cost minimization is utilized to examine the effect of climate on the energy demand by residential, commercial, transportation and industrial sectors using a transcendental logarithm cost function. The first order condition of cost function gives a sectorial compensated demand for energy and substitution elasticities between different sectors.

Cost minimizing framework for energy demand. Following Deaton and Muellbauer [52], the utility maximization is a function of energy consumption by residential, commercial, transportation and industrial sectors subject to the constraint that cost equals the quantity times the price of energy.

$$utility(u) = \max_{u \geq 0} \{(u) \text{ subject to } w.\, x = cost(c)\}$$
$$(or)$$
$$Maximize\ utility(u) = v(x) \text{ subject to } w.\, x = cost(c) \quad (1)$$

The dual problem of utility maximization is to minimize the cost of energy consumption subject to the constraint that the sum of sectoral consumption maximizes utility. This can be represented as:

$$utility(u) = \max_{u \geq 0} \{(u) \text{ subject to } w.\, x = cost(c)\}$$
$$(or) <$$
$$Maximize\ utility(u) = v(x) \text{ subject to } w.\, x = cost(c) \quad (2)$$

To examine the effects of climate z on the energy demanded Eq. (2) can be re-written to include climate variables as:

$$cost(c) = \min_{x \geq 0} \{(w*x,z) \text{ subject to } v(x,z) = utility(u)\} \quad (3)$$

The transcendental logarithm cost function with non-Hicks neutral technology is tested and assumed in this study. The non-Hicks neutral transcendental logarithm cost function is presented as:

$$\ln C = \alpha_0 + \sum_{i=1}^{I} \alpha_i \ln w_i + \sum_{k=1}^{K} \alpha_k \ln z_k + \frac{1}{2} sum_{i=1}^{I} \sum_{h=1}^{I} \gamma_{i,h} \ln w_i \ln w_h + \frac{1}{2} \sum_{k=1}^{K} \sum_{l=1}^{K} \gamma_{i,j} \ln z_k \ln z_l + \frac{1}{2} \sum_{i=1}^{I} \sum_{k=1}^{K} \gamma_{i,k} \ln w_i \ln z_k + \phi_t \, T + \frac{1}{2} \phi_{t,t} T^2 + \sum_{i=1}^{I} \phi_{i,t} \ln w_i * T + \sum_{k=1}^{K} \phi_{k,t} \ln z_k * T + \varepsilon \quad (4)$$

where C is the cost function; w is a vector of energy prices paid by residential, commercial, transportation and industrial sectors, T stands for technology change, and z stands for the average and variance of temperature and precipitation associated with negative deviations (downside) and positive deviations (upside) of the distribution.

The demand functions defined as the logarithmic first order conditions of the cost function is represented as:

$$\frac{\partial \ln C}{\partial \ln w_i} = CS_i = \alpha_i + \sum_{i=1}^{4} \gamma_h \ln w_h + \sum_{k=1}^{6} \beta_k \ln z_k + \phi_i \ln T + \varepsilon \quad (5)$$

Using the transcendental functional form implies that the following homogeneity and symmetry conditions are met is Eq. (5).

$$\sum \alpha_i = 1 \text{ and } \gamma_{i,h} = \gamma_{h,i} = 0 \quad (6)$$

The parameter coefficients from Eq. (5) helps in the computation of the cross price elasticities (CPE) of demand as:

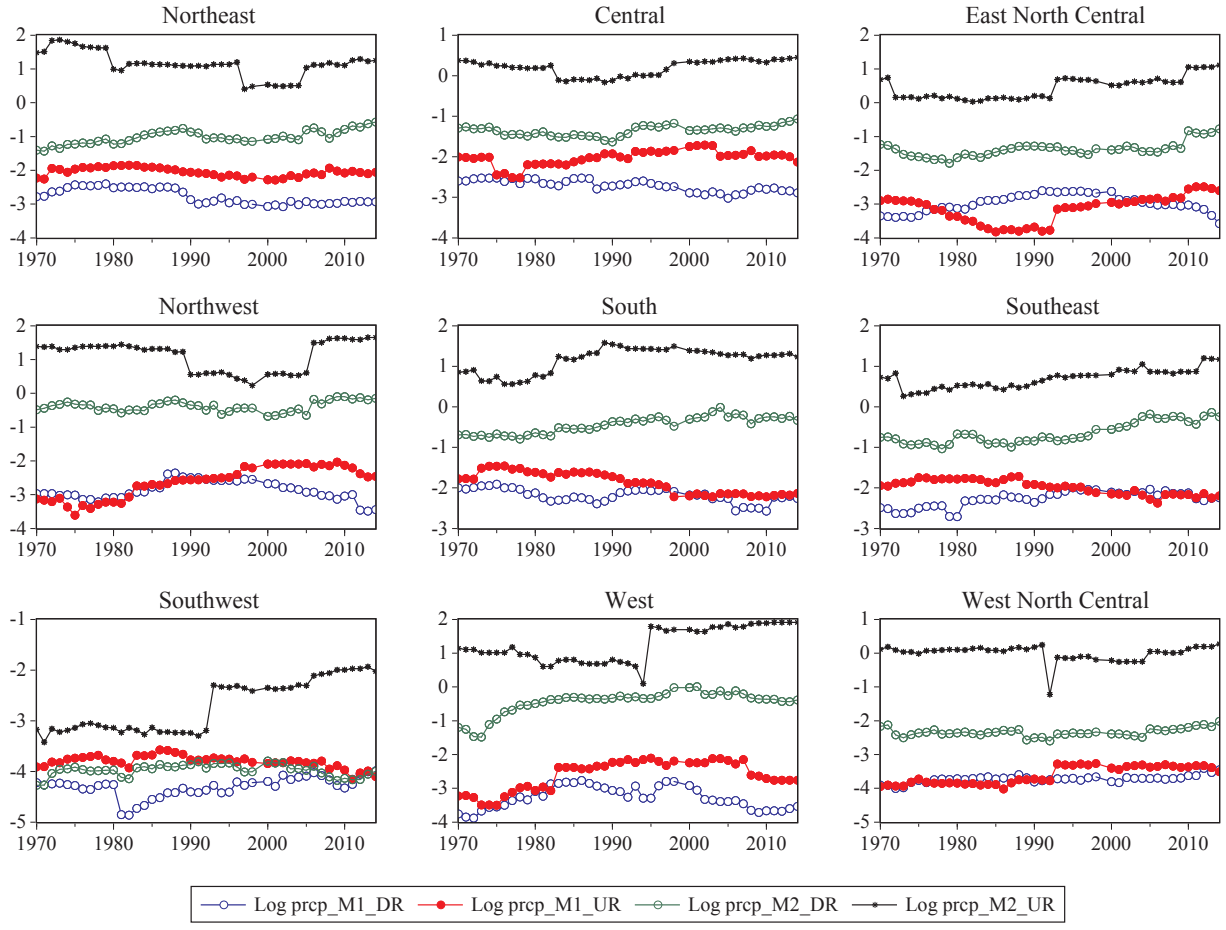

Fig. 5. Average and variance of downside and upside precipitation, 1970 to 2014.

$$\eta_{ih} = \frac{\alpha_{ih}}{CS_i} + CS_h \text{ and } \eta_{ii} = \frac{\alpha_{ii}}{CS_i} + CS_i - 1 \quad (7)$$

The parameter coefficients from Eq. (5) helps in the computation of Allen elasticities of substitution (AES) as:

$$\sigma_{ih}^{AES} = \frac{1}{CS_i CS_h} * \alpha_{ih} + 1 \text{ and } \sigma_{ii}^{AES} = \frac{1}{CS_i^2} * \alpha_{ii} (CS_i^2 - CS_i) \quad (8)$$

4. Data and variables used in the analysis

The U.S. Energy Information Administration (http://www.eia.gov) publishes the U.S. and state energy production and sectoral use accounts. To estimate the demand equations, the total energy expenditure, by residential, commercial, transportation and industrial sectors in millions of dollars were obtained for 48 continental states. The demand shares are computed from the total and individual expenditures. Also, the corresponding prices (dollars/million Btu) paid by the residential, commercial, transportation and industrial sectors for the same period were obtained for the above-mentioned states. The climate data on monthly temperature and precipitation were obtained from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/). The data obtained are used in the computation of average and variance of temperature and precipitation associated with negative deviations (downside) and positive deviations (upside) of the distribution based on the last 25 years. The unit of temperature is deg. F. to 10ths and precipitation is inches to 100ths.

Fig. 2 presents the average sectoral demand shares by climate region. The energy used by the transportation sector increased from 1970 to 2014 in all nine regions with the lowest and highest increase of 2.3 and 10% in the South and Central, respectively. While the energy used by the commercial sector showed a decline in seven of nine regions with South and West North Central being the exceptions. The highest decline of 26.4% in energy use by the commercial sector was seen in the Northeast and the lowest decline of 4.1% was seen in the West. The energy used by the industrial sector showed a decline in all nine regions from 1970 to 2014, with the highest decline of 23.9% (West North Central) and lowest decline of 3.7% (Southeast). The energy used by the residential sector declined in three regions - South, West North Central and Southwest by 6.7%, 3.9% and 0.8%, respectively. The remaining six regions showed an increase in energy use with the lowest and highest increase of 0.7% and 7.6% respectively in the Northwest and Northeast regions.

Table 1 summarizes the mean, standard deviation, minimal and maximal values for the demand prices and shares for 48 states from 1970 to 2014. Also, present in Table 1 is the summary statistics for the eight climate variables used in the analysis.

Fig. 3 presents the average prices of energy demanded by sector. Based on nominal dollars, the energy price increased by 128.9 (commercial), 106.8 (transportation), 106.3 (industrial) and 89.4 (residential)% across nine regions. The highest increase in the energy price of 155.2 (Northeast), 135.8 (West North Central), 112.6 (West) and 102.4 (Southwest)% were seen in the commercial, industrial, transportation and residential sectors, respectively. The lowest increase in the energy price of 76.8 (East North Central), 83.8 (Northeast), 94.5 (West North Central) and 102.7 (Central)% were observed in the residential, industrial, commercial and transportation sectors, respectively.

Fig. 4 presents the average temperature and variance of temperature associated with the negative deviations (downside) and positive deviations (upside) of the distribution. The average temperature with

Table 2
Estimated system of demand share equations for energy by climatic regions.

Parameter	Transportation		Industry		Residency	
	Estimate	P>|z|	Estimate	P>|z|	Estimate	P>|z|
			Northeast			
Intercept	0.4006	<.0001	0.2415	< .0001	0.2412	<.0001
Transportation	0.1455	<.0001	0.0061	0.6142	−0.0587	<.0001
Industry	0.0381	<.0001	−0.0606	<.0001	0.0103	0.0753
Residency	−0.1152	<.0001	0.1360	<.0001	−0.0005	0.9751
Commercial	−0.0707	<.0001	−0.0484	0.0044	0.0410	0.0003
Technology	0.0013	0.0028	−0.0034	<.0001	−0.0007	0.0370
Mean precipitation Downside	−0.2692	<.0001	−0.3338	<.0001	0.2087	<.0001
Mean precipitation Upside	0.2348	<.0001	0.0242	0.4970	−0.1575	<.0001
Variance precipitation Downside	−0.0287	<.0001	−0.0164	0.0489	0.0529	<.0001
Variance precipitation Upside	−0.0008	0.0409	0.0005	0.3296	0.0005	0.1485
Mean temperature Downside	0.0744	0.0023	−0.1306	<.0001	0.1104	<.0001
Mean temperature Upside	−0.1011	<.0001	0.0072	0.6051	0.0197	0.0345
Variance temperature Downside	0.0001	<.0001	0.0000	0.8411	0.0000	0.5211
Variance temperature Upside	0.0000	0.0035	−0.0001	<.0001	0.0001	<.0001
			Central			
Intercept	0.5160	<.0001	−1.0577	<.0001	0.2585	<.0001
Transportation	0.1527	<.0001	−0.2023	<.0001	0.0060	0.7225
Industry	0.0732	<.0001	0.0258	0.1447	−0.0662	<.0001
Residency	0.0076	0.0017	−0.0055	0.1022	0.0001	0.9365
Commercial	0.0198	0.2025	−0.0643	0.0030	0.0218	0.0284
Technology	0.0075	0.4441	−0.0277	0.0409	0.0104	0.0945
Mean precipitation Downside	0.0000	0.0160	0.0000	0.2364	0.0000	0.5778
Mean precipitation Upside	0.0000	0.0002	0.0000	0.0034	0.0000	0.3843
Variance precipitation Downside	0.4375	<.0001	0.2535	<.0001	0.2792	<.0001
Variance precipitation Upside	0.0041	0.7826	−0.1005	<.0001	0.2159	<.0001
Mean temperature Downside	−0.0188	0.2204	0.0246	0.0006	−0.0737	<.0001
Mean temperature Upside	0.1791	<.0001	−0.0523	<.0001	−0.0322	0.1133
Variance temperature Downside	−0.1454	<.0001	0.0860	<.0001	−0.0769	<.0001
Variance temperature Upside	−0.0037	<.0001	0.0018	<.0001	−0.0003	0.5071

Table 3
Estimated system of demand share equations for energy by climatic regions.

Parameter	Transportation		Industry		Residency	
	Estimate	P>|z|	Estimate	P>|z|	Estimate	P>|z|
			East North Central			
Intercept	0.0000	0.0021	0.0000	0.3273	0.0000	0.0180
Transportation	0.0000	0.1573	0.0000	<.0001	0.0000	0.0053
Industry	0.2789	<.0001	0.3060	<.0001	0.3764	<.0001
Residency	−0.0631	<.0001	−0.0950	<.0001	0.1661	<.0001
Commercial	0.1176	<.0001	−0.0356	0.0116	−0.0624	0.0026
Technology	−0.0125	0.5471	0.0702	<.0001	−0.0114	0.7990
Mean precipitation Downside	−0.0481	0.0100	0.0396	0.0121	−0.0552	0.1623
Mean precipitation Upside	−0.0010	0.0201	0.0001	0.7403	−0.0006	0.3933
Variance precipitation Downside	0.4448	<.0001	−0.1454	0.0511	0.1230	0.3358
Variance precipitation Upside	0.6559	<.0001	−0.2845	<.0001	−0.0212	0.7683
Mean temperature Downside	0.0069	0.6361	0.0092	0.4535	0.0200	0.0195
Mean temperature Upside	−0.0045	0.0500	0.0008	0.6781	0.0006	0.5330
Variance temperature Downside	−0.0333	<.0001	0.0092	0.1621	0.0021	0.7903
Variance temperature Upside	0.0045	0.4122	−0.0060	0.2011	0.0740	0.0005
			Northwest			
Intercept	−0.0413	0.2162	0.0077	0.7415	−0.0327	0.2810
Transportation	−0.0009	0.1396	0.0013	0.0010	−0.0037	<.0001
Industry	0.1423	0.1886	−0.0504	0.5039	0.4883	<.0001
Residency	−0.1464	0.0172	0.0361	0.3958	−0.2190	<.0001
Commercial	−0.0122	0.0905	−0.0022	0.6567	0.0372	0.0016
Technology	−0.0014	0.0809	0.0002	0.7348	−0.0091	<.0001
Mean precipitation Downside	0.0009	0.8932	0.0125	0.0076	−0.0260	0.3501
Mean precipitation Upside	−0.0724	<.0001	0.0092	0.4542	0.0606	<.0001
Variance precipitation Downside	0.0001	<.0001	0.0000	0.0515	0.0000	0.1095
Variance precipitation Upside	0.0000	0.2099	0.0000	0.6760	0.0000	0.1786
Mean temperature Downside	0.2113	<.0001	0.1004	0.0068	0.8503	<.0001
Mean temperature Upside	−0.0784	<.0001	0.2773	<.0001	−0.2435	<.0001
Variance temperature Downside	−0.0115	0.3400	−0.1672	<.0001	0.2571	<.0001
Variance temperature Upside	0.0488	0.0675	0.0471	0.2016	−0.2697	0.0001

Table 4
Estimated system of demand share equations for energy by climatic regions.

Parameter	Transportation		Industry		Residency	
	Estimate	P>|z|	Estimate	P>|z|	Estimate	P>|z|
			South			
Intercept	−0.0197	0.7045	0.0383	0.0591	0.0205	0.5829
Transportation	−0.1707	<.0001	0.0794	<.0001	−0.0341	0.0918
Industry	−0.0001	0.0009	0.0000	0.0002	−0.0002	<.0001
Residency	−0.0001	<.0001	0.0000	<.0001	0.0000	0.1486
Commercial	0.0014	0.9591	0.5808	<.0001	0.0801	0.0358
Technology	−0.0106	0.4128	0.1866	<.0001	0.0304	0.0809
Mean precipitation Downside	−0.0725	<.0001	−0.0146	0.2273	−0.0043	0.8391
Mean precipitation Upside	0.1802	<.0001	−0.1670	<.0001	−0.0316	0.2854
Variance precipitation Downside	−0.0645	0.0036	0.0216	0.2488	0.0271	0.4140
Variance precipitation Upside	−0.0022	0.0002	−0.0016	0.0046	−0.0019	0.0557
Mean temperature Downside	0.1444	0.0164	−0.4548	<.0001	0.8954	<.0001
Mean temperature Upside	−0.0134	0.6753	0.2007	<.0001	−0.0994	0.0808
Variance temperature Downside	0.0354	<.0001	0.0532	<.0001	−0.0623	<.0001
Variance temperature Upside	−0.0060	<.0001	−0.0105	<.0001	0.0143	<.0001
			Southeast			
Intercept	0.0120	0.1492	−0.0543	0.0001	0.0229	0.0792
Transportation	0.1273	<.0001	−0.0021	0.9136	−0.1242	<.0001
Industry	−0.0476	0.0003	−0.1180	<.0001	0.1177	<.0001
Residency	0.0020	<.0001	−0.0001	0.8441	−0.0034	<.0001
Commercial	−0.2281	<.0001	0.6651	0.0652	0.6789	0.0445
Technology	−0.1119	<.0001	0.3316	0.0784	−0.0545	0.7564
Mean precipitation Downside	−0.0041	0.3730	1.1799	0.0002	−0.1525	0.5950
Mean precipitation Upside	−0.0002	0.8624	−0.1016	0.0049	0.0284	0.3950
Variance precipitation Downside	0.0682	0.0087	0.0004	0.9756	0.0644	<.0001
Variance precipitation Upside	0.0011	0.9395	−0.0469	0.0003	−0.0614	<.0001
Mean temperature Downside	0.0001	<.0001	0.0000	0.1287	0.0000	0.7134
Mean temperature Upside	0.0000	0.1398	0.0000	0.1991	0.0000	0.6193
Variance temperature Downside	0.3696	<.0001	0.2459	<.0001	0.1726	<.0001
Variance temperature Upside	0.2199	<.0001	−0.0061	0.5926	−0.1013	<.0001

Table 5
Estimated system of demand share equations for energy by climatic regions.

Parameter	Transportation		Industry		Residency	
	Estimate	P>|z|	Estimate	P>|z|	Estimate	P>|z|
			Southwest			
Intercept	−0.7927	<.0001	0.0053	0.7583	−0.0216	0.1231
Transportation	0.1039	<.0001	0.0052	<.0001	−0.0003	0.7173
Industry	−0.0332	0.0002	−0.0079	0.6915	−0.0254	0.1148
Residency	0.0436	<.0001	−0.0347	0.1302	−0.0057	0.7569
Commercial	0.0001	<.0001	0.0000	0.9994	0.0000	0.3190
Technology	0.0000	0.0797	0.0000	0.0009	0.0000	0.2338
Mean precipitation Downside	0.4442	<.0001	0.2375	<.0001	0.2045	<.0001
Mean precipitation Upside	0.2530	<.0001	−0.0849	<.0001	−0.0892	<.0001
Variance precipitation Downside	−0.0811	0.0002	0.1292	<.0001	−0.0106	0.4374
Variance precipitation Upside	0.0224	0.4096	−0.0972	<.0001	0.0431	0.0186
Mean temperature Downside	−0.0749	0.0112	−0.0014	0.9522	0.0123	0.5220
Mean temperature Upside	−0.0067	<.0001	0.0027	<.0001	0.0028	<.0001
Variance temperature Downside	−0.4371	0.0206	0.3161	0.0368	0.2610	0.0367
Variance temperature Upside	0.0477	0.6450	0.0760	0.3630	0.0504	0.4639
			West			
Intercept	0.4442	<.0001	0.2375	<.0001	0.2045	<.0001
Transportation	0.2530	<.0001	−0.0849	<.0001	−0.0892	<.0001
Industry	−0.0811	0.0002	0.1292	<.0001	−0.0106	0.4374
Residency	0.0224	0.4096	−0.0972	<.0001	0.0431	0.0186
Commercial	−0.0749	0.0112	−0.0014	0.9522	0.0123	0.5220
Technology	−0.0067	<.0001	0.0027	<.0001	0.0028	<.0001
Mean precipitation Downside	−0.4371	0.0206	0.3161	0.0368	0.2610	0.0367
Mean precipitation Upside	0.0477	0.6450	0.0760	0.3630	0.0504	0.4639
Variance precipitation Downside	0.0053	0.7583	−0.0216	0.1231	−0.0327	0.0053
Variance precipitation Upside	0.0052	<.0001	−0.0003	0.7173	−0.0022	0.0051
Mean temperature Downside	−0.0079	0.6915	−0.0254	0.1148	0.0268	0.0453
Mean temperature Upside	−0.0347	0.1302	−0.0057	0.7569	0.0355	0.0211
Variance temperature Downside	0.000000	0.9994	0.0000	0.3190	−0.0001	0.0084
Variance temperature Upside	0.000041	0.1231	−0.00001	0.2338	−0.00003	0.0007

Table 6
Estimated system of demand share equations for energy by climatic regions.

Parameter	Transportation		Industry		Residency	
	Estimate	P>|z|	Estimate	P>|z|	Estimate	P>|z|
			West North Central			
Intercept	0.4667	<.0001	0.0960	0.0018	0.2706	<.0001
Transportation	0.1308	<.0001	0.0951	<.0001	−0.1388	<.0001
Industry	0.0168	0.3153	−0.1433	<.0001	0.0869	<.0001
Residency	−0.0335	0.3809	0.2462	0.0004	−0.0960	0.0045
Commercial	−0.0979	0.0001	−0.1221	0.0071	0.0955	<.0001
Technology	−0.0007	0.3489	−0.0015	0.2521	0.0004	0.5209
Mean precipitation Downside	0.8404	0.0039	−2.4655	<.0001	1.0788	<.0001
Mean precipitation Upside	−0.2092	0.3161	−0.3274	0.3790	0.4192	0.0224
Variance precipitation Downside	−0.0509	0.4714	−0.1279	0.3104	0.1856	0.0030
Variance precipitation Upside	−0.0070	0.0322	0.0018	0.7506	−0.0011	0.7054
Mean temperature Downside	−0.0021	0.6665	−0.0088	0.3099	0.0106	0.0133
Mean temperature Upside	−0.0397	<.0001	0.0366	0.0142	0.0040	0.5835
Variance temperature Downside	0.0000	0.0049	0.0000	0.0811	0.0000	0.1184
Variance temperature Upside	0.0000	0.0089	0.0000	0.5148	0.0000	0.8114

Table 7
Estimated energy demand price and substitution elasticities.

	Trans.	Indus.	Resid.	Comm.	Trans.	Indus.	Resid.	Comm.
				Northeast				
	Price Elasticities Based on Individual Shares							
Trans.	−0.229	0.259	−0.025	−0.005		C	S	C
Indus.	0.654	−1.294	1.298	0.131	S		C	S
Resid.	−0.031	0.630	−0.711	0.112	S	C		C
Comm.	−0.027	0.113	0.172	−0.258	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.254	1.765	−0.095	−0.077		C	S	C
Indus.		0.388	4.491	0.713			S	S
Resid.			0.001	0.581				S
Comm.				−0.463				
				Central				
	Price Elasticities Based on Individual Shares							
Trans.	−0.187	0.192	0.245	−0.250		C	S	S
Indus.	0.311	−0.836	1.000	0.088	S		C	S
Resid.	0.459	1.093	−1.030	−0.522	S	S		C
Comm.	−0.826	0.168	−0.911	1.569	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.246	0.766	1.131	−2.075		C	S	S
Indus.		0.064	4.658	0.670			S	S
Resid.			0.195	−4.488				S
Comm.				−2.141				

negative deviations increased from 1970 to 2014 across nine regions with the highest and lowest increase of 0.7 and 48.2%, respectively in the West North Central and Central regions. The average temperature with positive deviations declined in all regions except for the East North Central. The highest and lowest decline was observed in the Southeast (37%) and West (2.7%), respectively. The variance of temperature associated with negative deviations (downside) and positive deviations (upside) was mixed. Four (Northwest, Southeast, West and Northeast) of nine regions showed a decline in variance of temperature for negative deviations. Similarly, four (Northwest, West, Southwest and West North Central) regions show a decline in variance of temperature for positive deviations.

Fig. 5 presents the average precipitation and variance of precipitation associated with negative deviations (downside) and positive deviations (upside) of the distribution. In contrast, the average precipitation associated with negative deviations (downside) and positive deviations (upside) was mixed. Six (Northwest, Central, South, East North Central and Northeast) regions show a decline in average precipitation associated with negative deviations. Four (South, Southeast, Southwest and Central) regions show a decline in average precipitation associated with positive deviations. In contrast, the variance of precipitation associated with negative deviations (downside) and positive deviations (upside) show an increase except the Northeast.

5. Empirical application and results

The estimation of the system of demand equations are based on the step-wise algorithm using generalized least squares and maximum likelihood procedures developed by Bjorn [53] and implemented in stata by Nguyen and Nguyen [54].

The empirical model for system of demand share equations:

Table 8
Estimated energy demand price and substitution elasticities, cont'd.

	Trans.	Indus.	Resid.	Comm.	Trans.	Indus.	Resid.	Comm.
				East North Central				
	Price Elasticities Based on Individual Shares							
Trans.	−0.052	0.035	0.159	−0.141		C	S	S
Indus.	0.059	−0.234	0.183	0.161	S		C	S
Resid.	0.264	0.169	−0.462	0.030	S	S		C
Comm.	−0.418	0.259	0.051	0.109	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.332	0.143	0.658	−1.057		C	S	S
Indus.		−0.427	0.755	1.170			C	S
Resid.			−0.227	0.188				C
Comm.				−0.841				
				Southwest				
	Price Elasticities Based on Individual Shares							
Trans.	−0.168	0.060	0.168	−0.060		C	S	S
Indus.	0.138	−0.373	0.081	0.321	S		C	S
Resid.	0.424	0.085	−0.551	0.042	S	S		C
Comm.	−0.228	0.452	0.059	−0.283	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.182	0.291	0.875	−0.472		C	S	S
Indus.		−0.358	0.412	2.459			C	S
Resid.			−0.208	0.293				C
Comm.				−0.508				

Table 9
Estimated energy demand price and substitution elasticities, cont'd.

	Trans.	Indus.	Resid.	Comm.	Trans.	Indus.	Resid.	Comm.
				South				
	Price Elasticities Based on Individual Shares							
Trans.	0.118	−0.137	0.307	−0.287		S	C	S
Indus.	−0.249	0.296	−0.866	0.780	S		S	C
Resid.	0.680	−1.295	0.247	0.368	S	S		S
Comm.	−1.011	1.821	0.568	−1.378	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.438	−0.586	1.742	−2.712		C	C	S
Indus.		−0.745	−4.688	6.666			C	C
Resid.			−0.881	3.451				C
Comm.				0.441				
				Southeast				
	Price Elasticities Based on Individual Shares							
Trans.	−0.127	0.148	−0.155	0.134		C	S	C
Indus.	0.346	−0.846	0.030	0.409	S		C	S
Resid.	−0.294	0.043	−0.208	0.459	S	C		C
Comm.	0.403	0.475	0.745	−1.624	S	S	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.247	0.789	−0.684	0.917		C	S	C
Indus.		0.023	0.127	2.783			S	S
Resid.			−0.432	3.304				C
Comm.				0.662				

$$CS_{i,nt} = \alpha_i + \sum_{i=1}^{4} \delta_{ih} \ln w_{h,nt} + \sum_{k=1}^{6} \varphi_{ik} \ln z_{k,nt} + \lambda_t \ln T_{i,nt} + u_{i,n} + w_{i,nt} \quad (9)$$

where i represents residential, commercial, transportation and industrial sectors for demand share equations and $n = 1,...,N(states)$ and $t = 1,...,T(years)$;u are unobserved state-level effects; and w are the observation-specific random errors. The commercial sector price is used to normalize the demand equations and hold the homogeneity and symmetry conditions.

Eq. (9) is estimated for each region and the parameter coefficients along with the elasticities are presented. Projecting the potential effect of regional climate change on energy demand poses many technical

Table 10
Estimated energy demand price and substitution elasticities, cont'd.

	Trans.	Indus.	Resid.	Comm.	Trans.	Indus.	Resid.	Comm.
				Southwest				
	Price Elasticities Based on Individual Shares							
Trans.	−0.055	0.040	0.194	−0.179		C	S	S
Indus.	0.112	−0.689	−0.654	1.979	S		C	C
Resid.	0.474	−0.491	−0.354	0.371	S	S		C
Comm.	−0.564	1.851	0.455	−1.742	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.241	0.226	0.978	−1.157		C	S	S
Indus.		−0.134	−3.383	12.448			C	C
Resid.			−0.362	2.366				C
Comm.				0.764				
				West				
	Price Elasticities Based on Individual Shares							
Trans.	0.014	−0.011	0.239	−0.241		S	C	S
Indus.	−0.043	0.006	−0.446	1.227	S		S	C
Resid.	0.609	−0.358	−0.579	0.328	S	S		C
Comm.	−0.763	1.204	0.396	−0.837	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.270	−0.087	1.242	−1.553		C	C	S
Indus.		−0.720	−2.429	7.881			C	C
Resid.			−0.186	2.093				C
Comm.				−0.002				

Table 11
Estimated energy demand price and substitution elasticities.

	Trans.	Indus.	Resid.	Comm.	Trans.	Indus.	Resid.	Comm.
				West North Central				
	Price Elasticities Based on Individual Shares							
Trans.	−0.254	0.281	0.104	−0.130		C	S	S
Indus.	0.529	−1.386	1.259	0.172	S		C	S
Resid.	0.250	1.749	−1.409	−0.590	S	S		C
Comm.	−0.513	0.337	−0.811	0.987	S	C	S	
	Hicks-Allen Elasticities of Substitution Elasticities Based on Individual Shares							
Trans.	−0.160	1.163	0.548	−1.128		C	S	S
Indus.		0.486	7.243	1.400			S	S
Resid.			0.491	−5.354				S
Comm.				−1.644				

challenges. These include the time scale involved, there are many uncertainties affecting future energy demands that must be addressed even in the absence of potential climate change, including rates of economic growth and proliferation and efficiencies of energy using technologies. This paper uses a trend variable to capture technological change.

Tables 2–6 presents the historical relationship between climatic and weather conditions and energy demand for the four sectors across the nine climatic regions of the U.S. The constant terms indicate the level of non-climate-sensitive energy use while the trend variable in each model represents the average annual percent change in non-climatic-sensitive energy use over the period of the analysis. The constant term is positive and significant for all sectors in the Northeast except commercial, which is negative. The transportation and residential sectors in the Central Region have positive and significant constant terms but industrial is negative. The constant terms are not significant for the remaining regions except transportation in the Southwest which has a large negative coefficient (−0.7927). The coefficient of −0.7927 implies that a 1% rise in non-climate sensitive energy will decrease the sector's energy demand by 0.8%.

The trend variable is not significant in all the regions except the transportation and industrial sectors in the Northeast with coefficients (0.0013) and (−0.0034), respectively. Thus, a 1% increase in the efficiency of energy using technologies will increase the energy demand of the transportation sector by only 0.001% and will decrease industrial by 0.003.

Importance of climate variables on energy demand. The climatic variables used in the analysis are the upside and downside deviations of the mean, and the variance of precipitation and temperature. The energy uses in the Southwest, Northeast and South are sensitive to both the downside and upside deviations from the mean precipitation. The energy uses of the three sectors in the southwest are sensitive to both the downside and upside risk of precipitation. The coefficients of the downside deviations are positive and significant for the region's transportation, industrial and residential sectors (0.4442, 0.2375 and 0.2045), respectively. The coefficient of 0.4442 implies a 1% increase in the downside risk in precipitation will increase the region's transportation energy demand by 0.44%. The signs of the upside risks are all

negative as expected except in transportation. For instance, the coefficient of −0.0892 for residential implies that a 1% increase in the upside risk of precipitation will reduce residential energy use by 0.09% in the Southwestern U.S. The transportation and industrial sectors of the northeast also are sensitive to both the downside and upside risks of precipitation; and all with expected signs. The Central is the most sensitive region to the upside and downside risk of the variance of precipitation. The energy uses of the three sectors in the region are sensitive to the downside variance of precipitation while for the upside, it is only industrial and residential. This is followed by the Northeast with transportation and residential energy uses being sensitive to the downside.

The industrial and residential sectors are the most sensitive to the down side deviations from the mean temperature. They are significant in the Northeast, Central and South. A 1% rise in the downside deviation from the mean in the Northeast reduces industrial energy use by 0.13% while residential use goes up by 0.11%. The same pattern occurs in the South. A 1% rise increases residential energy use by about 0.9% but industrial use goes down by 0.45%. The direction is reversed in the Central region. A rise in the downside deviation from the mean temperature reduces residential energy use while industrial use rises. The upside deviations have a significant impact on the Northwest and Southwest energy use. Energy use by transportation, industrial and residential sectors are sensitive to this temperature variable. An increase in the upside deviation from mean temperature reduces the energy use in the transportation and residential sectors in the Northwest while industrial demand goes up. However, in the southwest, transportation goes down while the industrial and residential use goes up. The downside of the variance of temperature significantly affects the three sectors Central, South and Southeastern U.S. A rise in the downside deviation of temperature increases the energy use of the transportation, industrial and residential sectors of the Southeast as well as transportation and industrial in the South but residential use declines. Transportation and residential declines in the Central but industrial use goes up. Just like the down side of the variance, the up side affects all the sectors in the Southern Region. There will be a reduction in industrial use, but the transportation and residential sectors will see an increase. The industrial and residential sectors in the Northeast also will be affected. The industrial and residential sector will record a slight increase and decrease in energy use, respectively.

Energy demand cross-price and substitution elasticities. The results of the regional energy demand cross-price (CPE) and substitution elasticities are presented in Tables 7–11. The latter (Allen Elasticities of Substitution, AES) represent purely technical substitution possibilities while the former include income effects and therefore represent an economic substitution potential. Both the CPE and AES should have the same sign since the energy shares are positive. There is a high potential for energy substitution when the commercial price of energy rises. The commercial sector own-price substitution is greater than in most of the regions. For instance, the own-price elasticities are −1.742, −1.644, and −1.624 for the Southwest, West North Central and the Southeast, respectively. The coefficient of −1.742 implies that a 1% increase in the price of energy will lead to about 1.7% reduction in energy use of the commercial sector in the Southwest. The coefficient for that sector of the Central Region is 1.569. This implies a 1% increase in energy price will result in about a 1.6% increase in energy use. There also are strong substitutions towards industrial and residential in the Northeast, Central and West North Central Regions. But there is no substitution for transportation in all regions with only.05% reduction in the East North Central and energy expenditure rising by 0.95% as the price of energy goes up by 1%. There are much less substitutions among sectors except commercial for industrial in Central, West, and Southwest. The coefficient of 1.851 between commercial and industrial implies industrial energy will be for commercial by 1.85%, for a 1% increase in energy price and industrial energy expenditure will fall by 0.85% in the Southwest.

There is no own pure technical substitution among the sectors except commercial in Central and West North Central with −2.141 and −1.644. Holding prices constant, a 1% improvement in technological change reduces the commercial energy use by 2.1% and 1.6% in Central and West North Central Regions. Most of the sectors either complement or substitute in energy use. Commercial and transportation are weak complements in the Northeast and South while there are strong complementarities between commercial and residential in the Central and West North Central Regions. The coefficients of −4.488 and −5.354 imply that a 1% improvement in technological change in the commercial sector reduces residential energy use by 4.45% and 5.34 in Central and West North Central Regions, respectively. There are strong relative substitutions between commercial and industrial. The coefficients of 6.666, 12.448, and 7.881 imply that a 1% technology improvement in the commercial sector will lead to the residential sector substituting 6.67%, 12.45%, and 7.90% commercial energy in the South, Southwest and West.

6. Conclusion

This research set out to estimate residential, commercial, transportation and industrial sectors energy demand accounting for technology and price change along with changes in climate, i.e., average and variance of temperature and precipitation associated with negative deviations (downside) and positive deviations (upside). Second, energy demand cross-price elasticities (CPE) and Allen elasticities of substitution (AES) between residential, commercial, transportation and industrial sector's energy demand are estimated using the parameters coefficients from the system of demand equations. Third, potential differences on the impact of prices, technology and climate on sector energy demand across nine climatic regions of the U.S. are evaluated.

The Southwest, Northeast and South are sensitive to precipitation variables, especially the transportation and industrial sectors. The downside of the precipitation for example, increases the demand for energy in all sectors in the Southwest except commercial. The industrial and residential sectors are again the most sensitive to downside temperatures and are profound in the Northeast, Central and the South. Residential and industrial energy uses in these regions go up with the rise of downside deviations from the mean temperature. Temperature variability resulting from climate change will occur significantly in the Central, South and Southeastern U.S. affecting again, transportation, residential and industrial energy uses. The upside of the variance of temperature also affect the Northeast. Thus, out of the nine regions, the South, Southwest, Southeastern, Northeastern, and Central will be significantly affected. This affects the residential, industrial and transportation sectors differently. However, there are more substitutions (either economic or technical) in the commercial sector.

A 1% increase in commercial energy price reduces energy demand by 1.74%, 1.64% and 1.62% in the Southwest, West North Central and Southeast, respectively; and energy expenditure goes down by 0.74%, 0.64% and 0.62%. The transportation sector's energy use is the least responsive to price change. The commercial sector's energy demand is more responsive to technological change than the rest and it is prevalent in the Central and West North Central. A 1% improvement in technology reduces the commercial energy use in both regions by 2.1% and 1.6%. The same 1% improvement in that sector's technology will lead to the residential sector using 6.67%, 12.45% and 7.90% of commercial energy in the South, Southwest and West. Northeast, Central and Southeast are affected most by climate variables and do not have much technical substitution.

The findings of this study will be relevant in the development of a comprehensive energy policies across nine U.S. climatic regions based on the changes in the energy demand by residential, commercial, transportation and industrial sectors accounting for technology, price, and downside and upside climate variables. The results suggest the sectors in the Southwest, Northeast and South climatic regions should

consider crafting their own energy policies to precipitation due to the regions' energy demand sensitivity to downside precipitation. While energy policies in the Northeast, Central and the South climatic regions should be developed around temperature for their sensitivity to the downside temperatures. Thus, these energy policies should address the lower average precipitation and temperature. For the same reasons, energy policies in the Central, South and Southeastern should be around the downside variability in temperature. Overall, alternative energy policies should be developed by climatic regions and sectoral energy demand.

The results from the CPE and AES call for a robust alternative energy policy in the U.S. transportation sector. The sector is the least responsive to energy price changes. This may be due to the sector's dependence on fossil fuels compared to other sectors. There should be energy policy efforts to encourage the sector's use of other alternative sources of energy may include increasing the ethanol portion of gasoline at the pumps, the use electric cars, and other technologies. In conclusion, due to the regional climatic difference, regionals climate policy may make more sense than a national policy. This is due to the differential impacts on energy demand by a sector as climate differs from region to region.

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